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Merrill R. Kaufmann, Principal Plant Physiologist
Carleton B. Edminster, Principal Mensurationist
and
Charles A. Troendle, Principal Hydrologist
Rocky Mountain Forest and Range Experiment Station[1]

Abstract

Needle area of Engelmann spruce, subalpine fir, and lodgepole pine and leaf area of aspen are predicted from d.b.h. or tree height. Leaf area index can be calculated from stand basal area.

[1] *Headquarters is in Fort Collins, in cooperation with Colorado State University.*

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Management Implications

The ability to predict leaf area index from simple measurements has great potential for improving hydrologic and growth/yield models. Specific knowledge of leaf area index makes possible a far better understanding of water vapor loss, interception, CO_2 fixation, and radiation balance of forest stands. These processes are critical elements in hydrologic models and in understanding forest canopy and understory growth.

This study reports development of equations which permit calculating both total leaf area and effective projected leaf area for Engelmann spruce, subalpine fir, lodgepole pine, and aspen. Total leaf area is the area of all needle or leaf surfaces. Effective projected leaf area is the area of shadows cast by randomly oriented needles or leaves.

The leaf area equations utilize tree basal area, d.b.h., or tree height as independent variables. These data are easily measured and are routinely collected in forest management activities. Therefore, leaf area of subalpine forest trees can be readily determined.

Leaf area index is the ratio of leaf area to land area. Total and effective projected leaf area indices can be determined for the conifers using stand basal area as an independent variable. For aspen, basal area per tree is required, along with stand basal area, for predicting leaf area indices.

Introduction

Until recently, knowledge of leaf or needle area of trees was of little interest in forest research or management. Most studies of forest canopy processes were conducted at levels requiring little specific information about foliage surface. During the past few years, however, estimates of leaf area have become increasingly important. Models of physical and biological processes of trees and forests are being developed at levels requiring data that characterize canopy configuration and the amount of foliage involved in exchange processes.

Hydrologic models are based increasingly upon individual processes involved in the storage and movement of water in soil and plants. For example, some studies focus on the consumptive use of water by foliage of individual trees in the context of plant and environment interaction. Until recently, estimates of growth and yield of stands required knowledge of stand density and crown closure as indicators of site utilization (Munro 1974). Attention now is turning to yield of biomass and the efficiency of wood production in relation to amount of foliage (Waring et al. 1980).

The selection of methods for estimating leaf area depends upon the particular needs for leaf area data. For studying gas exchange or other processes on small amounts of foliage, accurate, direct measurements of leaf or needle area often are needed. In such cases, leaf area can be determined by measuring and counting individual leaves or needles, or foliage can be harvested at the end of the study for measurement with an electronic leaf area meter. For large trees, however, the measurement of individual leaves is impractical, and destructive sampling is often unacceptable. At the stand level, the only reasonable approach for estimating leaf area is the use of predictive empirical relationships.

One of the most useful and accurate methods of estimating leaf area of trees is based on a physiological relationship. Under normal conditions, the relative size of various plant parts remains balanced because the parts are physiologically interdependent (Kaufmann and Troendle 1981). Loss of water from foliage by transpiration requires that water be supplied through the sapwood conducting tissue in the trunk. Leaf area of the crown is limited by the capacity of the sapwood to supply water, because water stress limits foliage growth when the sapwood transport capacity is inadequate. Similarly, sapwood size is affected by the amount of foliage available to produce dry matter for trunk growth. A growing number of studies now demonstrate that a close relationship exists between leaf area and cross-sectional area of sapwood conducting tissue in the trunk (e.g., Gholz et al. 1979, Rogers and Hinckley 1979, Waring et al. 1977).

Recently, Kaufmann and Troendle (1981) showed that the leaf-area/sapwood-area relationship was the same for portions of the crown as it was for the entire crown in four subalpine tree species in the central Rocky Mountains. The study reported here was undertaken to determine the simplest relationships for estimating leaf area of subalpine tree species in the central Rocky Mountains using rapid and nondestructive measurement techniques. Attention was given to

selecting parameters for estimating leaf area that were readily available and related to forest management activities. During the past decade, considerable interest has developed in biological and physical processes at the individual tree level. Therefore, most of the results presented here characterize leaf area of trees as functions of individual tree variables. However, leaf area also can be related to stand characteristics such as basal area and size classification.

Methods and Materials

Trees were sampled at the Fraser Experimental Forest, 8 km southwest of Fraser, Colo., during August and September of 1979 and 1980. The sampling procedures summarized here are given in detail by Kaufmann and Troendle (1981). Data were collected on four subalpine tree species—Engelmann spruce (*Picea engelmannii* Parry), subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.), lodgepole pine (*Pinus contorta* var. *latifolia* Engelm.), and aspen (*Populus tremuloides* Michx.). Trees were selected from a wide range of stands and physiographic situations and represented a broad spectrum of size, age, and growth rate. Sample size ranged from 12 to 15 trees per species, and tree size ranged from small saplings several meters tall to large, mature trees (table 1).

Trees were carefully felled, and foliage samples were collected. For small trees, all the foliage was collected, including small branches. For the largest trees, fresh foliage exceeded 5 m^3 in volume, and subsampling was required (see Kaufmann and Troendle (1981) for details of the subsampling procedure). Foliage samples were dried for 1-5 days in a small insulated building equipped with electric heaters. This facilitated removal of the branches, which were discarded. Final foliage dry weight was determined after an additional period of at least 48 hours at 70-75° C.

Trunk measurements included total height, depth of live crown (difference between total height and height to base of live crown), and outside diameters and sapwood areas at breast height (1.37 m) and at the base of the crown. Leaf areas of tree crowns were determined by measuring the dry weight of all foliage (or estimating total dry weight from subsamples) and multiplying by a total leaf area : dry weight conversion factor. These factors were as follows (Kaufmann and Troendle 1981):

Engelmann spruce	9.996 $m^2 \cdot kg^{-1}$
Subalpine fir	8.859 $m^2 \cdot kg^{-1}$
Lodgepole pine	9.518 $m^2 \cdot kg^{-1}$
Aspen	21.94 $m^2 \cdot kg^{-1}$

The ratio of total leaf area to projected leaf area was determined for each species. The procedures used here for estimating projected leaf area differ from those apparently followed in other studies. Gholz et al. (1976) and other researchers appear to have determined the ratio by measuring the total area of conifer needles and then measuring the projected area of flattened needles. For example, Gholz et al. (1976) used a ratio of about 2.3 for western hemlock, Douglas-fir, and silver fir. Thickness of needles (compared to a flat leaf) could account for this 15% increase in area above that of two parallel planes having the same outline. Conventionally, total leaf area of angiosperms is twice the projected area.

Estimates of projected area of foliage obtained by this method assume that all foliage is oriented horizontally. In studies involving canopy processes, this assumption often is unacceptable. For example, attenuation of solar radiation passing through a canopy is dependent not on the projected area as determined above, but on the effective projected area, which is also dependent upon leaf orientation. Radiation intensity in the lower portion of a canopy is a function of the actual shadows cast by foliage in the upper canopy, not by the potential area of shadows if all foliage was oriented horizontally.

The equations given below provide methods for estimating total leaf area and effective projected leaf area. Total leaf area was estimated using the leaf-area : dry-weight conversion factors given above. Effective projected leaf area was determined by assuming random orientation of foliage. Kimes et al. (1979) concluded that needle orientation of lodgepole pine and probably many other conifers was random, although Norman and Jarvis (1974) provided data for Sitka spruce suggesting a nonrandom orientation. Perhaps aspen leaf orientation is nonrandom, but no data are

Table 1.—Sample size, maximum d.b.h., basal area per tree (BA), sapwood area at 1.37 m (SA), tree height (TH), and total leaf area (TLA) of the sample trees. Minimum d.b.h. was 1-3 cm, and minimum TH was 2-3 m

	Engelmann spruce	Subalpine fir	Lodgepole pine	Aspen[a]
Sample size	15	12	14	14
Maximum d.b.h. (cm)	51.1	49.8	49.8	42.7
Maximum BA (cm^2)	2,047	1,947	1,947	1,430
Maximum SA (cm^2)	1,242	363	662	461
Maximum TH (m)	32.5	30.2	29.6	26.5
Maximum TLA (m^2)	1,196	903	410	83.4

[a]*Includes only aspen trees sampled in this study. These data were pooled with those of Johnston and Bartos (1977) for all analyses.*

available describing orientation. However, errors associated with assuming random orientation of needles and leaves are likely to be small.

Effective projected leaf area was calculated by first measuring the actual projected area of horizontal needles or leaves. For spruce, fir, and pine, this projected area was measured without laying the needles flat—twists and curves were allowed to occur. By this procedure, the ratio of total needle area to actual projected area of horizontal needles was 3.21 for Engelmann spruce and subalpine fir and 3.34 for lodgepole pine. Random distribution of needles or leaves would result in leaf angles uniformly distributed between $-90°$ and $90°$ from the horizontal. Accordingly, the shadow cast by direct beam radiation may be determined as the cosine of this angle. Therefore, the mean shadow length, obtained by integrating the cosine over the range of from $-90°$ to $90°$, is 63.66% of leaf length. Finally, effective projected leaf area of randomly oriented foliage is calculated as 0.6366 times the actual leaf area for unflattened needles or leaves held horizontally. The ratios of total leaf area to effective projected leaf area are as follows:

Engelmann spruce	5.04
Subalpine fir	5.04
Lodgepole pine	5.25
Aspen	3.14

Standard stepwise regression techniques were used for analyses, with total leaf area as the dependent variable. Curves were forced through the origin. By this procedure, trees under 1.37 m tall are ignored when determining leaf area or leaf area index of stands. For many forest processes, this is suitable because very small trees behave as understory vegetation. Leaf area of small trees can probably be estimated using diameter measurements made near the ground. An extensive series of analyses evaluated single and multiple parameters for estimating leaf area. These parameters included diameter at breast height, basal area at breast height (a function of d.b.h.), diameter at the base of the crown, sapwood area at breast height, total tree height, and depth of live crown. After analyses were complete, equations were determined for both effective projected and total leaf areas using the appropriate ratios given above.

Results

A linear relationship between needle area and basal area per tree was observed for Engelmann spruce, subalpine fir, and lodgepole pine (figs. 1, 2, and 3). Equivalent tree diameters are indicated in the upper scale. Comparison of regression equations with tree basal area, total tree height, and depth of live crown as independent variables indicated that suitable estimates of needle area can be made simply using basal area measurements. Regression equations relating needle area to basal area are given in table 2. Because d.b.h. and basal area per tree are directly related [$BA = \pi$ (d.b.h./2)^2], needle area can also be determined directly from d.b.h. using a separate set of equations. These equations are also given in table 2.

Aspen data collected in this study were supplemented with those of Johnston and Bartos (1977) for 18 trees sampled in northern Utah and northwestern Wyoming. With the exception of two trees, the data were described by a curvilinear relationship of total leaf area to tree basal area (fig. 4 and table 2). The two trees not included in the analyses were sampled from an unusual site on the middle of a south-facing, 35% slope and characterized by a continuous moisture seep. These trees had very deep crowns and dense foliage, probably the combined result of a continuous supply of water and high visible radiation.

The relationship between leaf or needle area and tree height also was calculated (table 3). For subalpine fir and lodgepole pine, R^2 values were about as high for equations using tree height as for those using basal area, indicating that either equation is suitable for estimating needle area. For Engelmann spruce the R^2 value declined slightly from 0.904 to 0.869, and for aspen the R^2 value decreased from 0.944 to 0.867. For the latter two species, tree basal area or diameter measurements are slightly better than tree height for estimating leaf area.

The relationship of needle or leaf area to basal area per tree may be used to calculate leaf area index as a function of stand basal area. Leaf area index is the ratio of total or effective projected leaf area to the surface area of land, and the units are dimensionless (from $m^2 \cdot m^{-2}$). For the three conifers, leaf area index is independent of individual tree size, because leaf area per tree is a linear function of tree basal area. Leaf area index as a function of stand basal area for the conifers is given in figure 5. Appropriate equations relating leaf area index to stand basal area are given in table 4 (SI units) and table 5 (U.S. standard units).

In aspen, leaf area per tree is curvilinearly related to tree basal area (fig. 4). Consequently, the relationship of leaf area index to stand basal area varies with tree diameter class (fig. 6). Large trees have less leaf area per unit basal area, and a stand of large trees has a lower leaf area index than a stand of smaller trees with a comparable stand basal area.

Discussion

These results indicate that effective projected or total leaf area for the major subalpine tree species in the central Rocky Mountains can be estimated using easily measured variables. The equations presented above permit calculating total leaf area of a tree from diameter, basal area, or height. Leaf area index can be obtained from stand basal area. In cases where vertical distribution of foliage within the canopy is required, it is likely that trunk diameters within the crown would be suitable for estimating leaf area above the point of measurement, although appropriate equations have not been developed. Kaufmann and Troendle

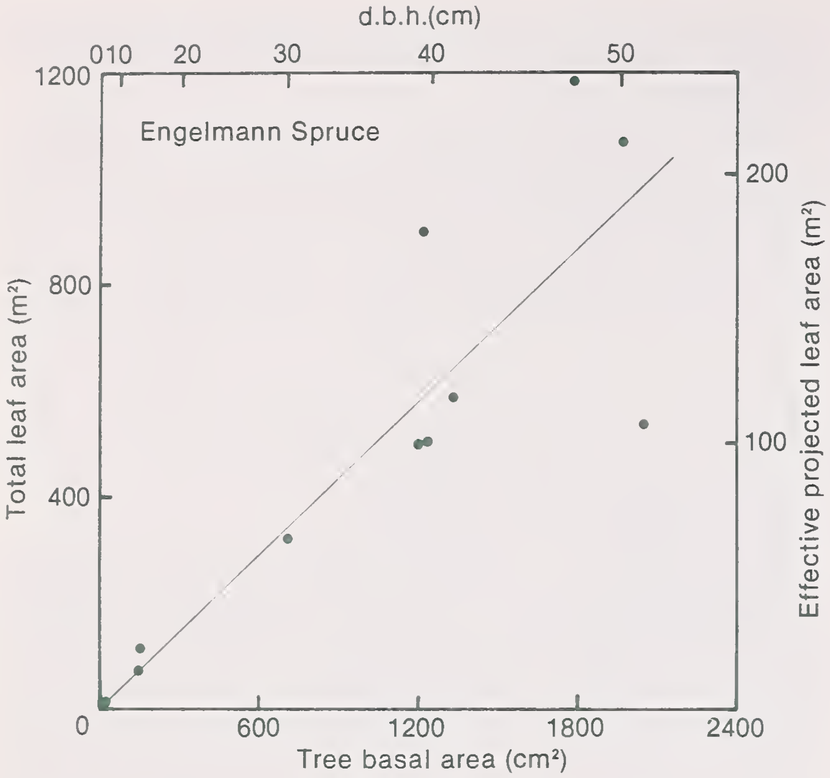

Figure 1.—Effective projected and total leaf (needle) area of Engelmann spruce as a function of tree basal area and d.b.h. See table 2 for appropriate regression equations.

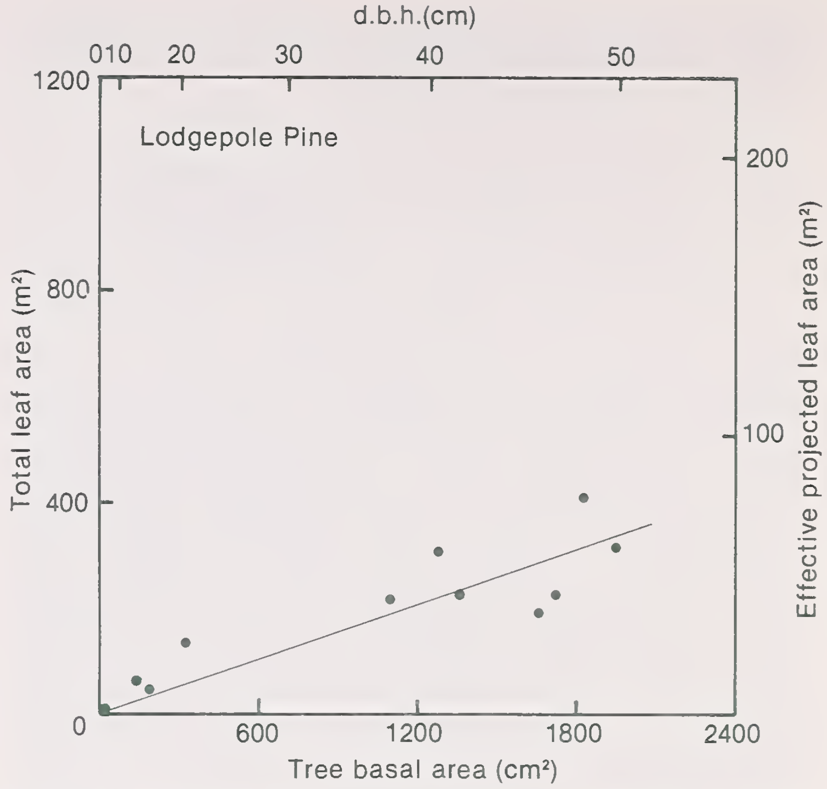

Figure 3.—Effective projected and total leaf (needle) area of lodgepole pine as a function of tree basal area and d.b.h. See table 2 for appropriate regression equations.

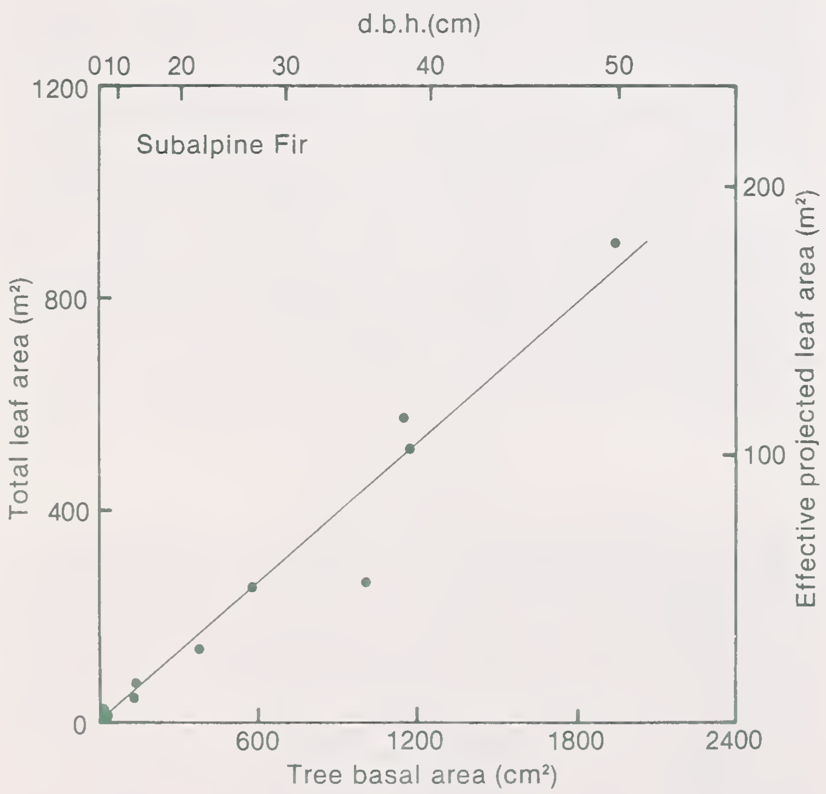

Figure 2.—Effective projected and total leaf (needle) area of subalpine fir as a function of tree basal area and d.b.h. See table 2 for appropriate regression equations.

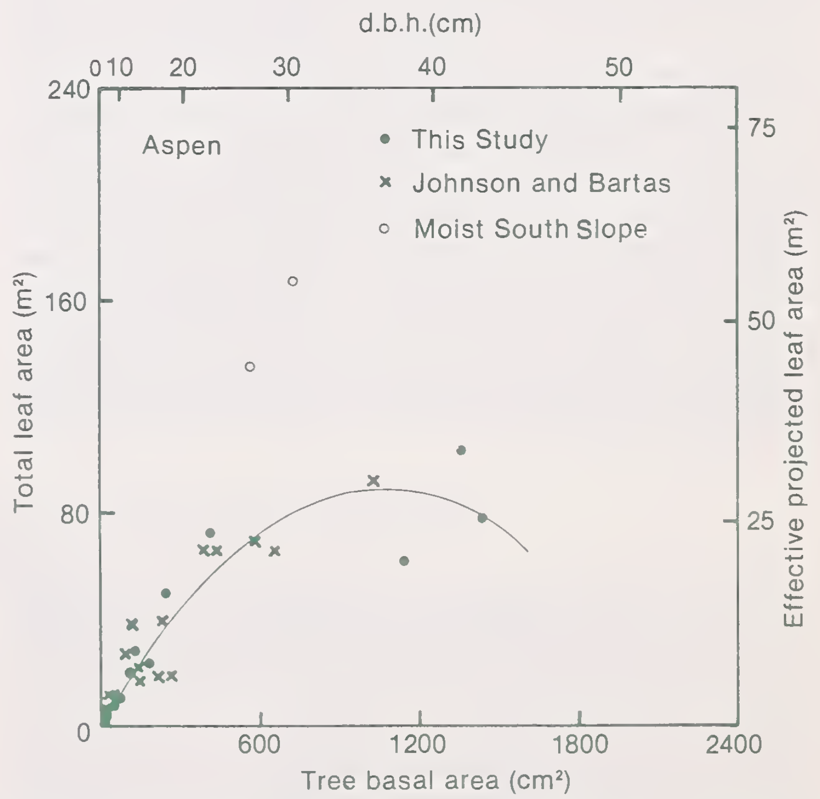

Figure 4.—Effective projected and total leaf area of aspen as a function of tree basal area and d.b.h. See table 2 for appropriate regression equations. Regression equations are based upon the combined data of this study and Johnston and Bartos (1977), but excluding the two trees located on the moist south slope.

Table 2.—Effective projected leaf area (EPLA) or total leaf area (TLA) as a function of basal area per tree (BA) or d.b.h. Leaf area is in m^2, BA is in cm^2, and d.b.h. is in cm

Species	Equation	$R^{2\,a}$	Standard error of estimate
Engelmann spruce	TLA = 0.483 BA	0.904	178.33
	TLA = 0.379 d.b.h.^{2}		
	EPLA = 0.0958 BA		
	EPLA = 0.0752 d.b.h.^{2}		
Subalpine fir	TLA = 0.437 BA	0.975	60.30
	TLA = 0.343 d.b.h.^{2}		
	EPLA = 0.0867 BA		
	EPLA = 0.0681 d.b.h.^{2}		
Lodgepole pine	TLA = 0.174 BA	0.930	55.99
	TLA = 0.137 d.b.h.^{2}		
	EPLA = 0.0331 BA		
	EPLA = 0.0261 d.b.h.^{2}		
Aspen	TLA = 0.168 BA − 0.0000787 BA^2	0.944	11.15
	TLA = 0.132 d.b.h.^{2} − 0.0000486 d.b.h.^{4}		
	EPLA = 0.0535 BA − 0.0000251 BA^2		
	EPLA = 0.0420 d.b.h.^{2} − 0.0000155 d.b.h.^{4}		

[a]*Although the coefficient of determination* (R^2) *for a zero-intercept model is technically undefined, it is included here for comparison of equations.*

Table 3.—Effective projected leaf area (EPLA) or total leaf area (TLA) as a function of tree height (TH). Leaf area is in m^2, TA is in m

Species	Equation	$R^{2\,a}$	Standard error of estimate
Engelmann spruce	EPLA = 0.1931 TH^2		
	TLA = 0.975 TH^2	0.869	208.2
Subalpine fir	EPLA = −2.292 TH + 0.2701 TH^2		
	TLA = −11.574 TH + 1.364 TH^2	0.974	64.39
Lodgepole pine	EPLA = 0.0791 TH^2		
	TLA = 0.416 TH^2	0.920	59.73
Aspen	EPLA = 0.996 TH		
	TLA = 3.126 TH	0.867	16.80

[a]*Although the coefficient of determination* (R^2) *for a zero-intercept model is technically undefined, it is included here for comparison of equations.*

Table 4.—Effective projected leaf area index (EPLAI) or total leaf area index (TLAI) as a function of stand basal area (SBA) and tree basal area (BA). Leaf area index is in $m^2 \cdot m^{-2}$, SBA is in $m^2 \cdot ha^{-1}$, and BA is in cm^2

Species	Equation
Engelmann spruce	EPLAI = 0.0958 SBA
	TLAI = 0.483 SBA
Subalpine fir	EPLAI = 0.0867 SBA
	TLAI = 0.437 SBA
Lodgepole pine	EPLAI = 0.0331 SBA
	TLAI = 0.174 SBA
Aspen	EPLAI = 0.0535 SBA − 0.0000251 SBA · BA
	TLAI = 0.168 SBA − 0.0000787 SBA · BA

Table 5.—Effective projected leaf area index (EPLAI) or total leaf area index (TLAI) as a function of stand basal area (SBA) and tree basal area (BA). Leaf area index is in $ft^2 \cdot ft^{-2}$, SBA is in $ft^2 \cdot acre^{-1}$, and BA is in ft^2

Species	Equation
Engelmann spruce	EPLAI = 0.0220 SBA
	TLAI = 0.111 SBA
Subalpine fir	EPLAI = 0.0199 SBA
	TLAI = 0.100 SBA
Lodgepole pine	EPLAI = 0.00760 SBA
	TLAI = 0.0399 SBA
Aspen	EPLAI = 0.0123 SBA − 0.00535 SBA · BA
	TLAI = 0.0386 SBA − 0.0168 SBA · BA

(1981) demonstrated that leaf area above any level in the crown may be estimated by measuring sapwood area at the base of the level. Because sapwood area and total cross-sectional area are well correlated, suitable estimates of leaf area using nondestructive diameter measurements are possible.

Values of total leaf area index for the subalpine tree species examined here agree well with those observed in other parts of North America. The maximum basal area of Engelmann spruce-subalpine fir stands is about 90 $m^2 \cdot ha^{-1}$; typically stands are composed of 90% spruce and 10% fir.[2] Total leaf area of these stands is 40 to 45 $m^2 \cdot m^{-2}$ (fig. 5). Gholz et al. (1976) reported total leaf areas of 42 $m^2 \cdot m^{-2}$ for mature stands of western hemlock and silver fir stands in the western Oregon Cascades.

In contrast, the maximum stand basal area of lodgepole pine in the central Rocky Mountains is about 70 $m^2 \cdot ha^{-1}$.[2] The total leaf area index of these stands is about 12 $m^2 \cdot m^{-2}$ (fig. 5), compared with values of 8-9 $m^2 \cdot m^{-2}$ for dry western hemlock and Douglas-fir sites (Gholz et al. 1976). Maximum leaf area indices for aspen were about 13 $m^2 \cdot m^{-2}$, and most stands were no higher than 9-12 $m^2 \cdot m^{-2}$ (fig. 6).[3] Total leaf area indices for eastern deciduous forests are typically 8 to 12 $m^2 \cdot m^{-2}$ (Whittaker 1966).

[2]*Personal communication with Robert R. Alexander, Chief Silviculturist, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.*

[3]*Personal communication with Wayne D. Shepperd, Research Silviculturist, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.*

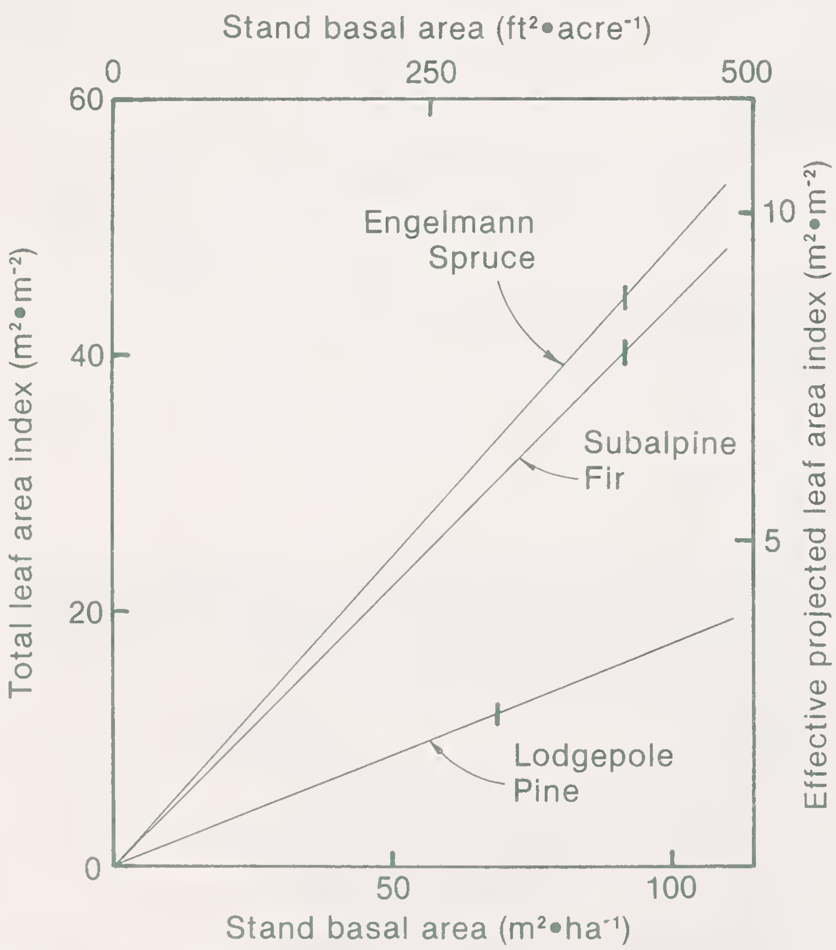

Figure 5.—Effective projected and total leaf area index as a function of stand basal area. Vertical slashes indicate normal upper limit for basal area of each species in the central Rocky Mountains.

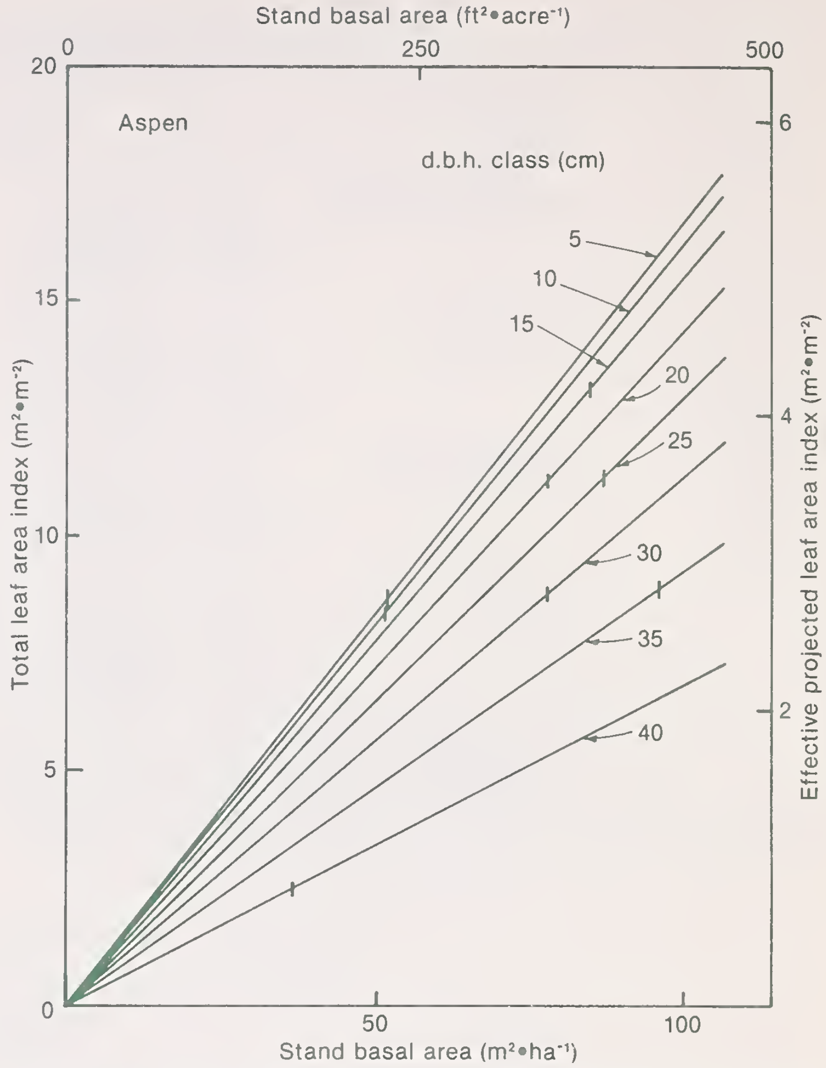

Figure 6.—Effective projected and total leaf area index of aspen as a function of stand basal area and tree diameter. Vertical slashes indicate upper limit for basal area by diameter in a large number of Colorado aspen stands (personal communication with Wayne D. Shepperd, Research Silviculturist, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.).

In some coniferous species (e.g., loblolly pine), needles persist for only 2 or 3 years. For such species, the total amount of foliage may vary considerably through a given year as a result of needle senescence and growth of new needles. For the three subalpine conifers studied here, needles persist for 7-20 years. Therefore, changes in needle area caused by seasonal variations in needle senescence and growth are masked by the large total amount of foliage. For aspen, however, the equations given above are for trees with fully expanded foliage. During the several-week period of leaf expansion in early June, leaf areas are below those predicted by the equations.

Species differences in leaf area index may affect understory vegetation and processes. For spruce-fir stands having high basal areas, little solar or visible radiation penetrates through the canopy to the forest floor. Consequently, only the most shade-tolerant tree species can become established in the understory. While the forest floor is often moist in such stands, low light intensity limits growth of ground cover species. Furthermore, evaporation from the soil surface is probably low because little solar energy is available.

In lodgepole pine and aspen stands, solar and visible radiation intensity beneath the canopy is greater than in spruce-fir stands. However, considerable differences in environmental conditions may exist at the forest floor beneath pine and aspen stands, even when the projected leaf area indices of the overstory are equal. Pine stands in the central Rocky Mountains are often characterized by dry litter and minimal understory vegetation. Dry litter and low amounts of vegetation may indicate high rate of evaporation at the soil surface, as a result of substantial shortwave radiation reaching the forest floor.

Similar visible and shortwave radiation probably reaches the forest floor beneath aspen stands, although the thin leaf structure of aspen may result in higher radiation levels beneath the canopy because of transmission through the leaves. Leaf orientation also may favor less interception of radiation by aspen leaves than by pine needles, particularly at solar noon if leaves tend to be oriented vertically. Aspen stands are almost always characterized by more dense understory vegetation, including conifer regeneration if seed sources are available. Dense understory vegetation may result from plant establishment early in the growing season, when decomposing litter and high soil surface moisture supplies create good seedbed conditions for germination. Furthermore, the aspen overstory canopy often leafs out after the understory begins to grow, thus giving the understory vegetation an early environmental advantage it would not have beneath a conifer canopy.

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Keywords: Needle area, leaf area index, d.b.h., basal area, tree height, Engelmann spruce, subalpine fir, lodgepole pine, aspen

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Rocky
Mountains

Southwest

Great
Plains

U.S. Department of Agriculture
Forest Service

Rocky Mountain Forest and Range Experiment Station

The Rocky Mountain Station is one of eight regional experiment stations, plus the Forest Products Laboratory and the Washington Office Staff, that make up the Forest Service research organization.

RESEARCH FOCUS

Research programs at the Rocky Mountain Station are coordinated with area universities and with other institutions. Many studies are conducted on a cooperative basis to accelerate solutions to problems involving range, water, wildlife and fish habitat, human and community development, timber, recreation, protection, and multiresource evaluation.

RESEARCH LOCATIONS

Research Work Units of the Rocky Mountain Station are operated in cooperation with universities in the following cities:

Albuquerque, New Mexico
Bottineau, North Dakota
Flagstaff, Arizona
Fort Collins, Colorado*
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Tempe, Arizona

*Station Headquarters: 240 W. Prospect St., Fort Collins, CO 80526